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Pillar: MM

U.S. DEPARTMENT OF ENERGY
SMARTMOBILITY
Systems and Modeling for Accelerated Research in Transportation

Multi-Modal Energy Analysis for Inter-City Freight Movement

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Argonne NATIONAL LABORATORY | INL Idaho National Laboratory | BERKELEY LAB | OAK RIDGE National Laboratory | NREL NATIONAL RENEWABLE ENERGY LABORATORY

OVERVIEW

Timeline

- Project start date: October 1, 2017
- Project end date: September 30, 2019
- Percent complete: 75%

Budget*

- Total project funding:
  – DOE share: 100%
  – Contractor share: 0%
- Funding for FY 2018: $680,000
- Funding for FY 2019: $384,000

*Funding levels are for all labs and tasks. FY 2018 funding included tasks completed in FY 2018 and not presented here.

Barriers

- Complexity of large-scale, multi-modal, integrated transportation networks
- Opportunities, challenges, and risks presented by emerging technologies and services
- Determining the impact of emerging technology on freight energy productivity

Partners / Collaboration

- NREL (lead)—Alicia Birky (principal investigator), Kyungsoo Jeong, Yi Hou, Venu Garikapati, Kevin Walkowicz
- Argonne National Laboratory (Joann Zhou)
- Texas A&M Transportation Institute
- University of Illinois at Chicago
- INRIX
- Coordination with SMART MM 3.1, AFI 4,1

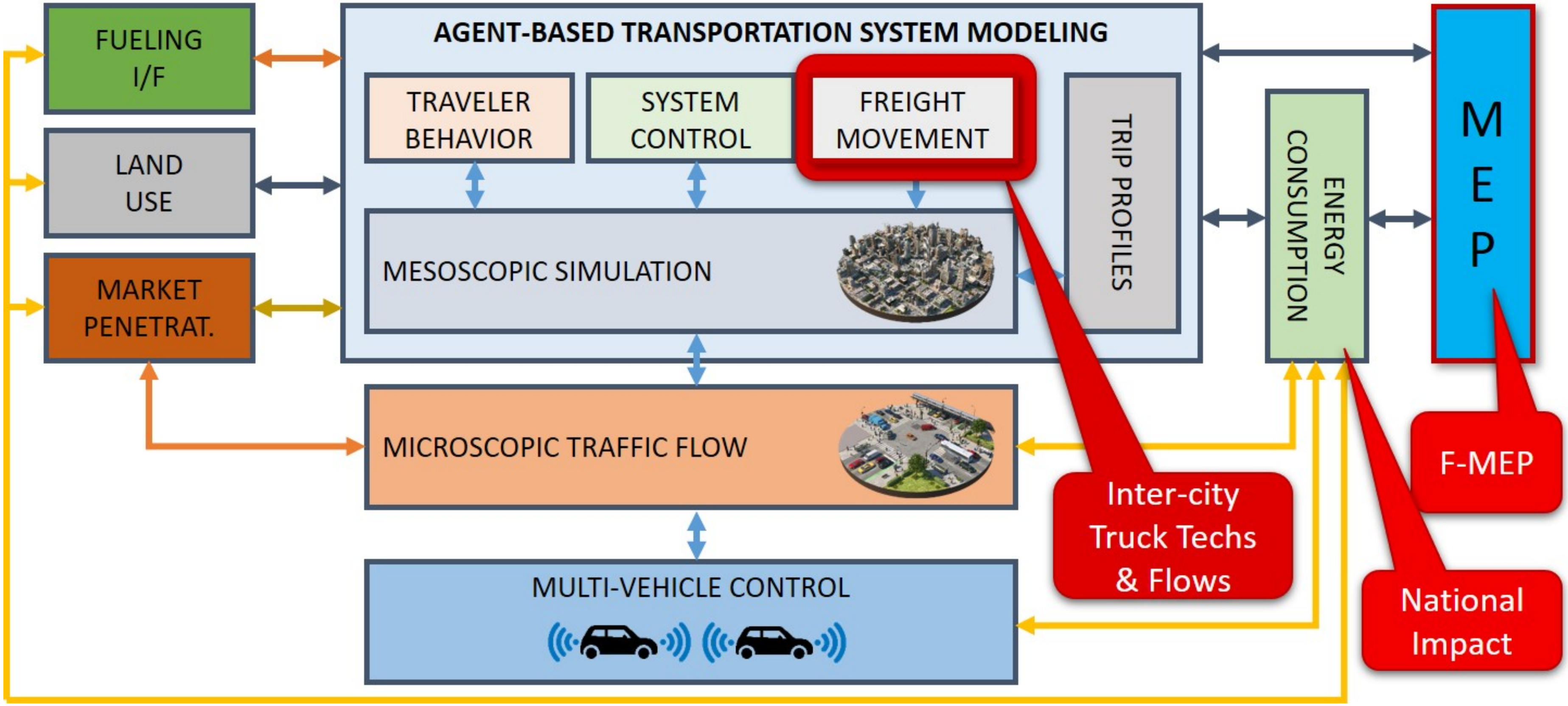
RELEVANCE

- **Overall objectives:**
  - Analyze energy reduction opportunities and challenges provided by new technologies and services in inter-city freight movement; identify areas for strategic R&D
  - Create tools and methods that can be applied to other research questions and other geographic areas to address national and regional freight energy productivity
  - Establish repeatable methods for quantifying energy impacts of new technologies to enable efficient goods movement for inter-city freight
  - Support larger SMART effort through analysis of inter-city freight movement regional impacts
- **FY 2019 focus:**
  - Develop multi-modal energy models and analysis tools of inter-city freight movement incorporating national freight demand and regional detail for Chicago
  - Develop metrics for inter- and intra-city freight mobility energy productivity (F-MEP)
  - Assess national and Chicago regional energy savings opportunity space in inter-city freight movement for selected “stand-alone” technology scenarios
  - Research questions:
    - How will the inter-city freight baseline mode shares and energy use profiles shift with projected increases in freight volumes with business as usual in 2040?
    - What effect could select technologies have on inter-city freight energy, time, and cost for region or nationally?
- **Impact:**
  - Quantification of the inter-city freight energy reduction opportunity space to define the regional and national energy impacts of SMART transport of freight and inform public and private sector decision makers

RELEVANCE

Relationship to Workflow

END-TO-END MODELING WORKFLOW



Supports workflow by supplying inter-city truck flows by type to mesoscopic simulation and measurement of scenario impacts on freight mobility energy productivity

MILESTONES

Date	Type	Milestones Go/No-Go	Status
Mar 2019	Quarterly Progress	Multi-modal inter-city freight model network updates complete. Provide preliminary truck flows into and out of Chicago freight establishments	Complete
Jun 2019	Quarterly Progress	Calibrated truck flow estimates for Chicago	On track
Sep 2019	Annual Milestone	Draft paper(s) documenting the multi-modal model and reporting results of stand-alone analyses of selected technology scenarios	On track
Sep 2019	Annual Milestone	Final version (2.0) of intra-city F-MEP	On track

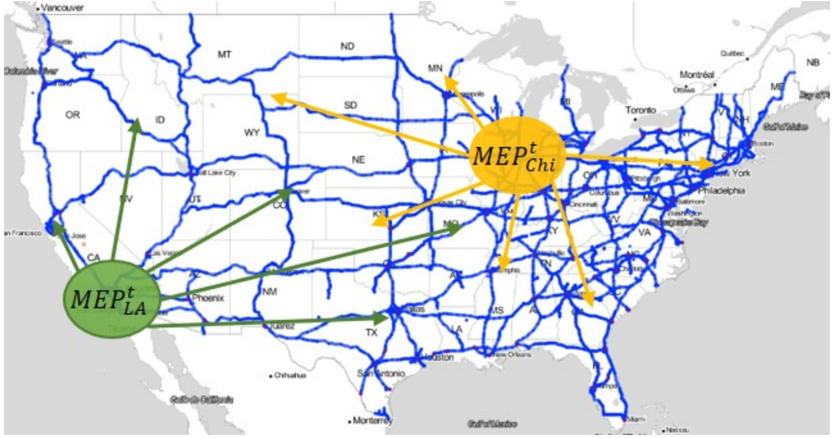
APPROACH

Multi-Modal Modeling and Analysis

- **Maintain consistency across other freight modeling and analysis efforts within SMART**
  – Comply with Freight Analysis Framework (FAF) zoning structure and methodologies
- **Specify scenarios for analysis**
  – Collect data on current and projected inter-city freight movement and emerging technologies
  – Leverage FY 2018 multi-modal work and add greater detail
    - Higher geographical and temporal resolution
- **Methodology to convert freight demand (tons, ton-miles) to truck flows, translated from FAF**
  – Characterize national truck movements at sub-FAF-zone level
  – Characterize truck movements into/out of Chicago counties
- **Develop multi-modal inter-city freight energy model to allow analysis of Chicago regional and national impact of emerging technologies.**
  – Build off FY 2018 MM freight energy optimization model
  – Incorporate time, energy, and cost into mode/route choice objective functions
  – Develop coarse cost models including elements impacted by scenario technologies; main focus on trucks
  – Calibrate to FAF and INRIX truck movement data
- **Apply the multi-modal inter-city model to evaluate scenarios with energy consumption for optimized inter-city freight movement**
  – Altered truck types, energy, cost, freight mode shares
  – Assess national and Chicago regional impacts
- **Develop framework to extrapolate Chicago regional impacts to other regions**

APPROACH
Freight Mobility Energy Productivity

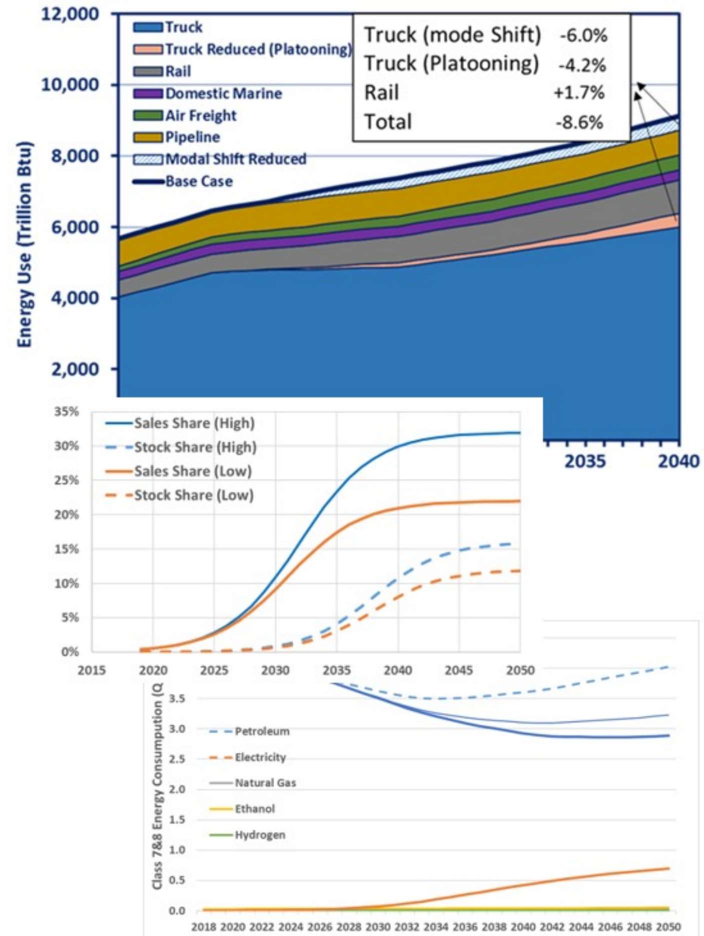
- **A measure of the quality of freight mobility for a region (e.g., city)**
  - Nationally generalizable and useful for inter-regional comparisons
  - Address freight-specific goals, needs, and costs, which differ from passenger mobility; include energy
  - Specified using available data, for all modes
  - Responsive to model scenarios
- **Shipper perspective, consistent with passenger MEP (mobility opportunities for a traveler at a given location)**
- **Separate approach for inter- and intra-city**
- **Intra-city F-MEP**
  - Begin with passenger MEP framework
- **Inter-city F-MEP**
  - New conceptualization based on gravity model
  - Mobility (accessibility) to other cities from originating city



TECHNICAL ACCOMPLISHMENTS AND PROGRESS

Scenario Development

- Scenarios based on prior work in FY 2018 with greater modeling detail
  - Shift to rail
  - Electrified vehicles (BEV, PHEV, HEV)
  - Various levels of vehicle automation
  - Connectivity and truck-load efficiency
- Higher geographical and temporal resolution
  - County-level for Chicago area
  - County aggregation to sub-FAF zone for national analysis
  - Peak and off-peak hourly average truck movements on major inter-city highway networks
- Shift to rail
  - FY 2018: optimize energy
  - FY 2019: optimize objective function (time, cost, energy) specific to commodity
- Platooning (automation)
  - FY 2018: national total platoon-able miles based on time at speed
  - FY 2019: temporally and geographically proximal
- Connectivity and truck-load efficiency
  - FY 2018: load pooling with no consideration of shipment / load size
  - FY 2019: Reduction in partial loads (load pooling) and empty miles of travel

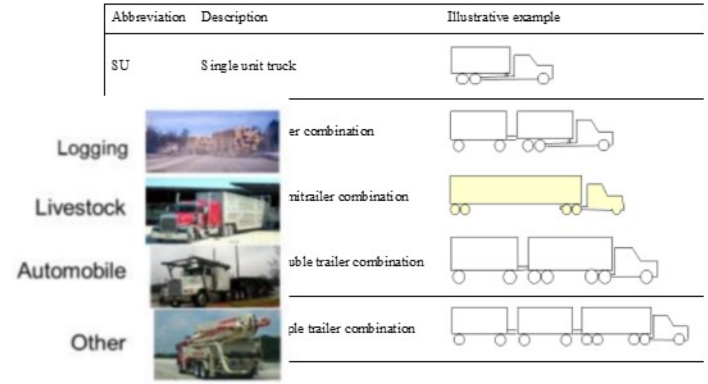


Higher modeling detail and resolution to address real-life freight system complexities

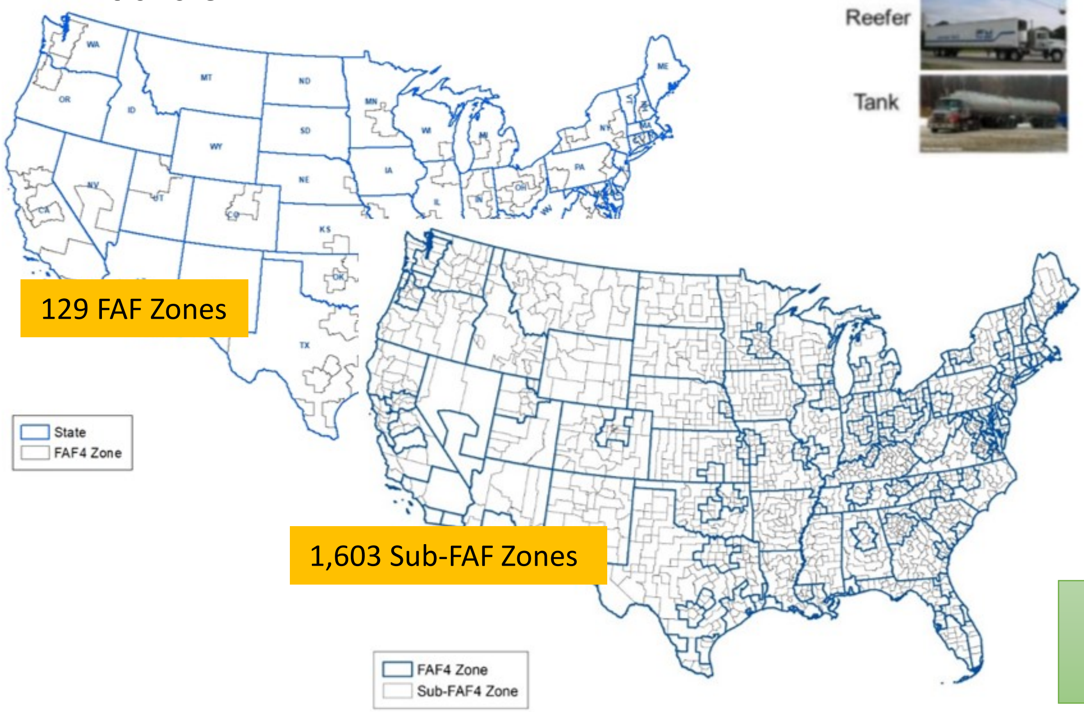
TECHNICAL ACCOMPLISHMENTS AND PROGRESS

Methodology: Convert Tons to Trucks and Disaggregate Geographically

- Freight tonnage to trucks
  - Adopt FAF methodology published in 2016
  - 45 truck/body configurations with average payload determined by commodity
  - Accounting for trips moving empty trucks/ trailers



Source: Maks Inc. (2016) FAF[4] Freight Traffic Assignment



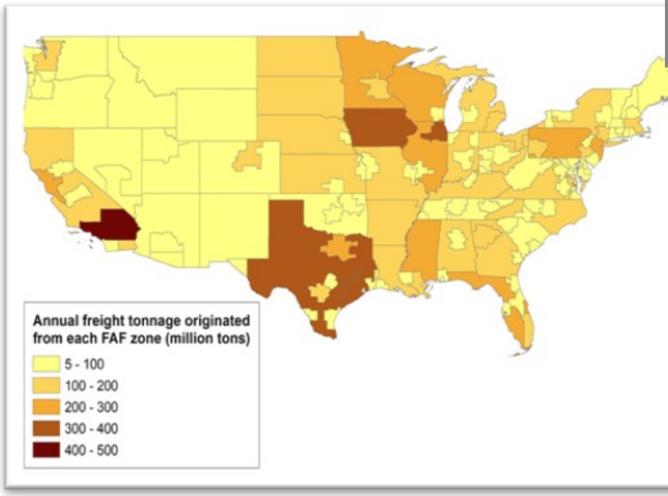
- New zoning system defined with higher geographic resolution
- 129 FAF zones, 1,603 sub-FAF zones, 3,109 counties
  - Population
  - Employment rate
  - Adjacency / spatial proximity

Methodology for truck movements at sub-zone level complete

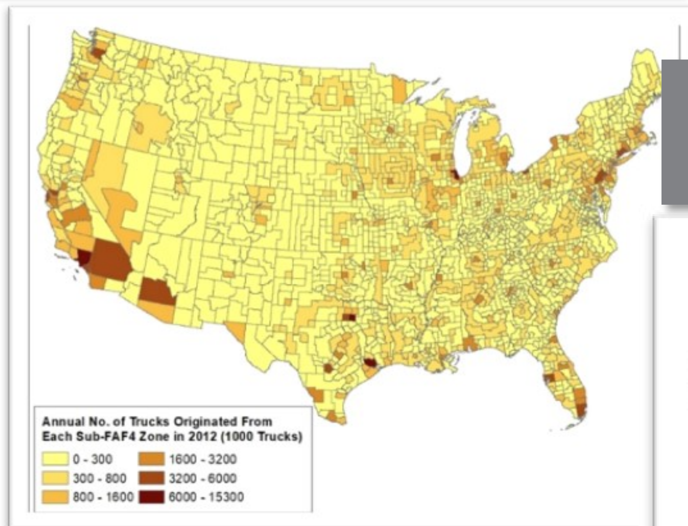
TECHNICAL ACCOMPLISHMENTS AND PROGRESS

Tons at FAF Zone to Trucks at Sub-FAF Zone and Chicago Counties

Annual fright tonnage originated from each sub-FAF zone in 2012



Annual number of trucks originated from each sub-FAF zone in 2012



Aggregate zip code–level establishments from U.S. Census–County Business Patterns, with NAICS detail and employment

Annual trucks from each Chicago county in 2012

The methodology developed will be applied to the multi-modal freight model tonnage results to generate truck flows for input to mesoscopic modeling

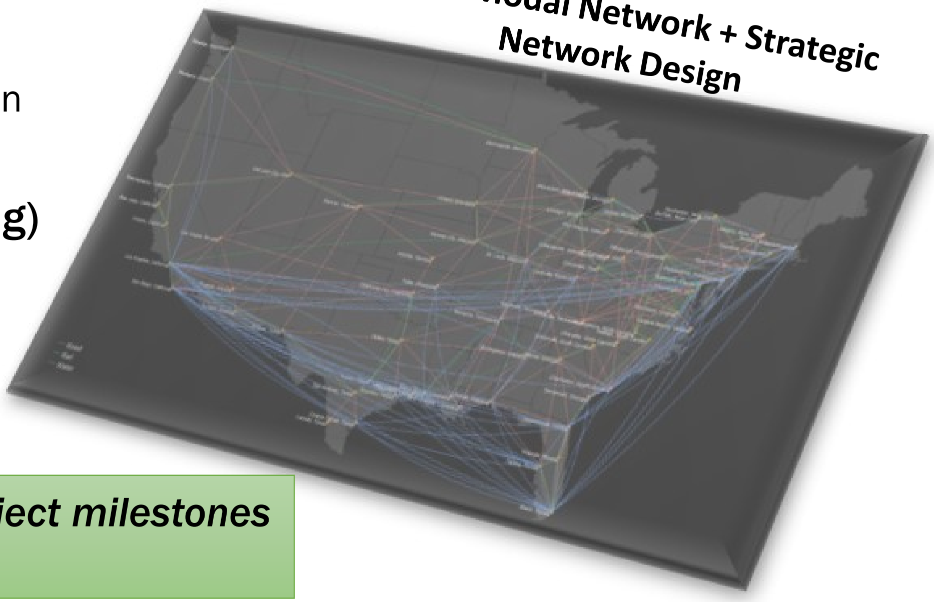
TECHNICAL ACCOMPLISHMENTS AND PROGRESS

Multi-Modal Inter-City Freight Energy Model

- **Data collection (completed)**
  - FAF commodity/vehicle flow data
  - Freight cost related data
- **Network**
  - Multi-modal/commodity network (completed)
  - Strategic network design (ongoing)
- **Network model specification (completed)**
  - Bi-level optimization problem
  - Upper level: minimize total energy consumption
  - Lower level: minimize total cost
- **Model assessment/enhancement (ongoing)**
  - Model calibration/validation
  - Modification of formulation
- **Coarse cost models (ongoing)**

FY 2018 Network

Multi-Modal Network + Strategic Network Design



Model development is on track to meet project milestones and deliverables

TECHNICAL ACCOMPLISHMENTS AND PROGRESS

Intra-City Freight MEP

- **Version 0.1 adopting framework from passenger MEP; completed Q1**
  - o_{ijkt} denotes the number of delivery opportunities of type j that can be reached by mode k from the i^{th} cell block (location) within a given travel time t (the isochrone)
  - The total opportunity is a weighted sum based on relative frequency of deliveries for each opportunity type:

$$O_{ikt} = \sum_{j} o_{ijkt} \cdot \frac{N^*}{N_j} \cdot \frac{f_j}{\sum_j f_j}$$

N^* = total number of benchmark opportunities across multiple cities

N_j^* = total number of opportunities of type j within the subject region

f_j = the typical frequency of deliveries for opportunity type j

  - Region MEP:

$$MEP_i = \sum_{k} \sum_{t} \left(o_{ikt} - o_{ik(t-10)} \right) \cdot e^{U_{ikt}}$$

U_{ikt} = function of energy and freight objective variables (e.g., energy, time, cost)

  - Opportunity typology, benchmark, and freight objective variables TBD

Intra-city F-MEP primary objective: capture impacts of technological advancements in goods movement within a city

TECHNICAL ACCOMPLISHMENTS AND PROGRESS

Inter-City Freight MEP

- **Isochrone approach from MEP and intra-city freight not applicable to inter-city**
- **Framework based on gravity model completed Q2**
  - MEP for originating city (i) by mode (k) to for destination cities j:

$$MEP_i^k = \sum_c \sum_j D_{cj} \cdot f_{c,ij}^k$$

i = originating city

k = mode (truck, rail, air, water)

c = commodity

j = destination region / zone

l = distance range

P = mode k share of commodity c

D = demand for commodity c in destination region j

f = freight mobility productivity measure

$$f_{c,ij}^k = e^{(\alpha e_k + \beta p_k) \cdot r_{ck}^l \cdot s_{ik}}$$

e = energy intensity (kWh/ton-mile)

r= proportion of commodity c movements

p = cost for mode k ($/ton-mile)

s = ease of shipping by mode k

l = distance range

α, β = weighting parameters

The inter-city F-MEP method is capable of providing metrics at different resolutions (e.g., aggregate, commodity-specific, mode-specific)

RESPONSES TO PREVIOUS YEARS REVIEWERS COMMENTS

- **…the project has so far only quantified impacts from a very limited set of freight approaches and still has a long way to go in terms of addressing the universe of applications.**
  - With Texas A&M Transportation Institute, the team is scoping emerging technologies and trends within "clusters" that determine appropriate modeling frameworks that could be applied to more complex scenarios.
- **… needs more commercial partners …additional freight shipping company partners would add to the project. One potential partner/advisor would be the American Trucking Associations who publish annual freight forecasts.**
  - The project has added the Texas A&M Transportation Institute and is relying on multiple industry reports and data sources. Team members are sharing results and looking for feedback through other DOE and laboratory collaborations, including the 21st Century Truck Partnership and the new Truck Laboratory Consortium. However, the project would benefit from greater participation and review by the shipping industry (carriers and shippers).
- **…possible that the associated budget will not be sufficient …consider more funding to complete project.**
  - Additional funding was received in late FY 2018 and in FY 2019.

COLLABORATION AND COORDINATION WITH OTHER INSTITUTIONS

- NREL (lead)
  - Collaborate on scenario definition
  - Multi-modal inter-city freight model
    - Development and calibration
    - Application to analysis of stand-alone technologies and regional impacts (bounding)
  - Freight MEP
- Argonne National Laboratory
  - Collaborate on scenario definition
  - FAF freight analysis methodology
    - Tons to trucks
    - Geographic disaggregation, FAF sub-zone definition
    - Temporal disaggregation
  - National scenario analysis
- University of Illinois at Chicago
  - Geographic disaggregation
  - Develop results in TransCAD
- Texas A&M Transportation Institute
  - Modeling framework whitepaper
  - Review of and input to F-MEP
- INRIX
  - Truck movement data: into, out of, around Chicago
- Coordination with SMART MM 3.1, AFI 4.1
- Indirect data providers:
  - U.S. Department of Transportation, U.S. Census, Bureau of Labor Statistics
  - IHS
  - American Trucking Associations, American Transportation Research Institute
  - Surface Transportation Board
  - Others

REMAINING CHALLENGES AND BARRIERS

- Data availability for cost models and F-MEP
  - Complexity of freight industry structure, decisions, and operations
  - Poor visibility into truck (and other mode) load factors and empty movements
  - Metrics for ease of shipping / capacity by mode
- Extrapolation of Chicago regional impacts to other regions dependent on results from mesoscopic freight modeling, which may not be available until late in Q4
- Estimation of weighting parameters in F-MEP
  - Consistent with passenger MEP, leave the matter to the judgment of user

PROPOSED FUTURE RESEARCH

- FY 2019
  - Synthesize literature and existing models to support F-MEP metrics and cost model data needs (ongoing)
  - Demonstrate use case of F-MEP framework(s) (Q4)
  - Calibrate MM freight model (ongoing)
  - Apply model to technology scenarios (late Q3–Q4)
  - Extrapolate regional impacts focusing on framework; apply first to MM freight inter-city model outputs until mesoscopic are available
- Proposed FY 2020+
  - Apply model and F-MEP framework to multi-technology scenarios
  - With industry partners (truck equipment manufacturers, shippers, carriers), refine F-MEP framework for industry use
  - Expand and refine model to apply to other regions (e.g., San Francisco, Columbus)
  - With industry and university partners, improve freight data and methodologies to reduce uncertainty
    - Consumer travel behavior and e-commerce
    - Freight commodity, tonnage relationship to truck trips (e.g., load factors, empty back haul)

Note: Any proposed future work is subject to change based on funding levels

SUMMARY

- Inter-city freight movement is a critical component of the economy and takes place within a complex multi-modal transportation network
- Emerging technologies and services are transforming this landscape, presenting opportunities, challenges, and risks with respect to energy consumption and meeting demand for freight movement
- This task is developing methodologies, models, analysis tools, and metrics to assess the quality of inter-city freight mobility and the potential impact of emerging technologies on energy demand both regionally and nationally
- These methods and tools will be applicable across regions, technologies, and research questions
- The project is on track to complete model development and apply the methodology to assess the impact of select emerging technologies
- The research team has a strategy to address remaining challenges

QUESTIONS?

TECHNICAL BACK-UP SLIDES

MULTI-MODAL INTER-CITY FREIGHT ENERGY MODEL

Network Model Specification

Upper level: Minimize Total Network Energy Consumption

$$\min f(\mathrm{A}, \mathrm{X}^*, E)$$

Subject to:

$$\alpha_{p,s} = \begin{cases} 1 \\ 0 \end{cases}, \qquad \forall\, p \in P \;\forall\, s \in S$$

$$TC_s^* \leq TC_s, \qquad \forall\, s \in S$$

Lower level: Minimize Total Network Cost

$$\min f(W, \mathrm{X}, C_p^k, T_p^k)$$

Subject to:

$$C_p^k = f(p, k)$$

$$T_p^k = f(p, k, x_p^k)$$

$$(1 - \delta_p^k) x_p^k \leq 0, \qquad \forall\, p \in P \;\forall\, k \in K$$

$$x_{o,d}^k = \sum_{p \in (o,d)} x_p^k, \qquad \forall (o,d), \quad \forall\, k \in K$$

$$x_p^k \geq 0, \qquad \forall\, p \in P \;\forall\, k \in K$$

Notation

A: Binary array representing the availability of alternative paths

$\alpha_{p,s}$: *1* if path p is routable in the multi-modal network scenario s; *0* otherwise

TC_s^*: Total cost of the optimal solution at the lower level problem for a given scenario s

TC_s: Total cost for a given scenario s

X^*: A set of the optimal path flow at the lower level problem

E: A set of parameters for the calculation of energy consumption

S: A set of multi-modal network scenarios

P: A set of alternative paths

W: Weight factors for cost and time

C_p^k: Total cost function of path p when moving one unit of commodity k

T_p^k: Total time function of path p when moving x_p^k

δ_p^k: *1* if path p is routable for commodity k; *0* otherwise

x_p^k: flow of commodity k over path p

$x_{o,d}^k$: Total flow of commodity k for a pair of o-d

X: A set of the path flow